

MONITORING PHYSIOLOGICAL SIGNALS DURING RUNNING EXERCISE

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Abstract—An ambulatory monitoring device for the measurement of heart rate, step rate and respiration signals of human subjects during running exercise is described. The monitor which is fixed on an elastic belt can be worn around the subject's chest. A new Microchip PIC16F876-20 8bit Flash Programmable Microcontroller with built-in A/D converters is used to sample analogue signals and transmit them wirelessly to a computer via RF transceivers. With 2.4GHz frequency hopping spread spectrum technology, the RF transceivers provide immunity to jamming as well as multi-path fading. The transmission power is 100mW that covers a range of approximately 1km line-of-sight. The monitor can also receive data from the computer for adjusting analogue circuit parameters and provide an audio click sound to the subject as a step reference signal through an earphone. It is hoped that, in the future, this ambulatory device will contribute to research studies on human performance during running exercise.

Keywords – Ambulatory monitoring, heart rate, step rate, running

I. INTRODUCTION

The final aim of this study is to investigate the coupling of heart rate and step rate of human subjects during running exercises. It is hypothesised that entrainment of heart rate and step rate during running may enhance the performance of the cardiovascular system under specific conditions [1] [2]. In the first place, we need a system that can obtain the runner's heart rate, step rate and be able to give a click sound as a reference signal for the subject to pace his steps during running. This paper details the development of an ambulatory monitoring device we designed that satisfies these requirements.

II. HARDWARE DESIGN

The ambulatory monitoring device developed consists of a front-end analogue circuit board, two RF transceiver modules and a computer. Fig. 1 shows a block diagram of the system. The analogue circuit board together with ECG electrodes, strain gauges and an accelerometer are all fixed on an elastic belt that can be worn around the subject's chest. One of the RF transceivers is clipped on the subject's waist belt and is connected

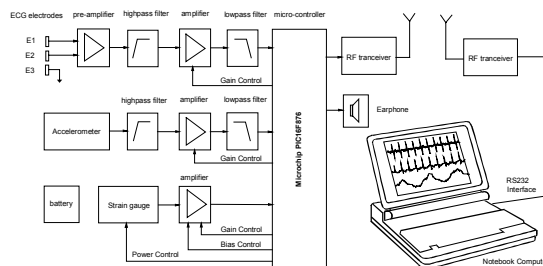


Fig. 1. System configuration

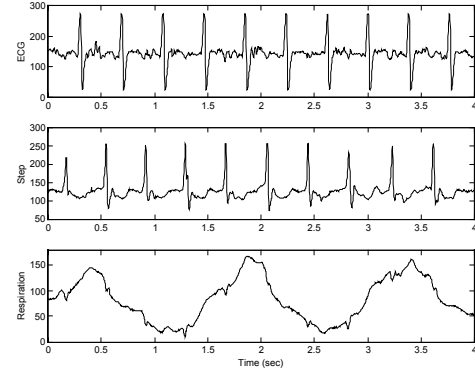


Fig. 2. Typical recorded physiological signals

to a micro-controller on the analogue circuit board through two-wire asynchronous serial interface.

A. Front-end Analogue Circuit

On the analogue circuit board, three channels of physiological signals are filtered, amplified and then sampled at 500Hz. A three-electrode ECG signal [3] is recorded for calculating the heart rate. In order to eliminate the baseline wandering, the ECG signal is differentiated by an analogue filter with a frequency response shown in Fig. 3. An accelerometer is used to measure step rate. According to [4], the majority of frequency components during running varied between 1 - 18 Hz in the vertical direction at the ankle. However, the frequency content of acceleration profiles was smaller at the low back than at the ankle. The frequency content of vertical body accelerations at the low back ranges from 0.7 – 4 Hz during trampoline jumping. But the impact between foot and the ground is less in trampoline jumping than in running. We found that a bandwidth of 0.16 – 5.0 Hz for step rate signal (see Fig. 3) was good enough for reliable step detection during running. The strain gauges attached on the elastic belt are used to measure the respiration signal by sensing the variation in the chest circumference. Since the resistance of the strain gauge is only 120 ohm, the power supply to the strain gauges is switched on only during analogue to digital (A/D) conversion time in order to reduce the power consumption. This is also the reason why the strain gauge signal is only amplified and offset but not filtered. A filter would increase the settling time required after the strain gauge is powered up and before the A/D conversion. The gains for these three analogue channels and the bias voltage for the strain gauge amplifier are controlled by the micro-controller through a quad digital potentiometer.

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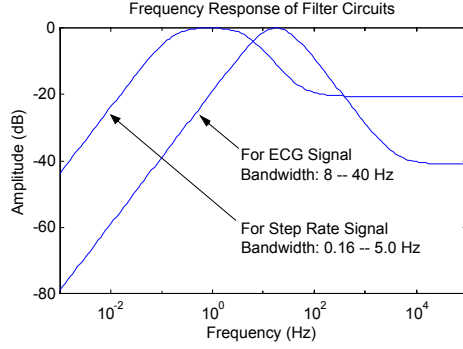


Fig. 3. Simulated frequency responses of analogue filter circuits.

A single rail power supply +5V is adopted for the analogue circuit. In order to measure the signal dynamics, the signal has to be biased to +2.5V. Therefore +2.5V is defined as a virtual ground for the analog circuit. It's maintained by obtaining +2.5V from a resistor divider and pass it through a voltage follower. The voltage follower was capable of absorbing the maxim current inflow from the virtual ground. Rail to rail operational amplifiers were used to maximized the dynamic range of the signal.

The micro-controller is PIC16F876-20 from Microchip, USA. It has built-in analogue to digital converter (ADC) and RS-232 serial communication interface. The flash program memory allows in-circuit reprogramming of the firmware. Although the ADC has a 10-bit resolution, only 8-bit is used in order to simplify the firmware program design and minimize the RF transmission time. The micro-controller also generates a click sound through an earphone as a step reference signal to the subject.

B. Data Transmission

Two WIT2400 RF transceiver modules from Digital-Wireless are adopted for RF connection. With 2.4GHz frequency hopping spread spectrum technology, this transceiver provides immunity to jamming as well as immunity to multi-path fading. The transmission power is 100mW which covers a range of approximately 1km line-of-sight. The transceiver's interface is RS-232 style with standard CMOS signal levels, which makes the electronic integration with the micro-controller and PC much easier. Using Automatic Retransmit Request (ARQ) in combination with a 6K buffer, this RF transceiver provides reliable error-free communication with up to 115.2Kbps full duplex data rate (57.6K is used for this project).

Since communication of the micro-controller and PC with the RF transceivers is transparent byte-oriented data stream, data is packetized before being sent to the RF module for wireless transmission and de-packetized after receiving them from the transceivers. Each packet consists of eight bytes. The first byte is a header and the following seven bytes are data. To distinguish the header from the following data, the most significant bit of the header is set to one. The first most significant bits of the

following seven data bytes are shifted to the seven unused bits of the header. Then they are cleared as zeros. At the receiver side, a header can be detected when the most significant bit of the received byte is one. Following the header are the seven data bytes which can be recovered easily by shifting the seven bits from the header back to the most significant bits of the seven data bytes.

III. SOFTWARE DESIGN

The software can be separated into two parts: the firmware running in the micro-controller on the front-end analogue circuit board and the application program running on PC.

A. Firmware Design

Since the sampling frequency for the analogue channel is 500Hz, the firmware are designed to do the following tasks in every 2ms:

- Conversion of analogue signals (ECG, acceleration, respiration and battery voltage) to digital values.
- Heartbeat and step detection. Heart rate and step rate calculation.
- Automatic gain control for analogue channels, synchronization of audio click sound to heartbeat with specified phase delay, and output control for the audio click sound.
- Preparation (packetization) of the collected data and then transmission of them through the serial communication interface.
- Reception, interpretation and execution of commands from the serial communication interface.

1) Heart Beat Detection

A commonly used algorithm for heartbeat detection is to square and filter the signal, then compare it with a threshold. The threshold can be adjusted by calculating the RMS (square-mean-root) of the signal in a moving window wide enough to include at

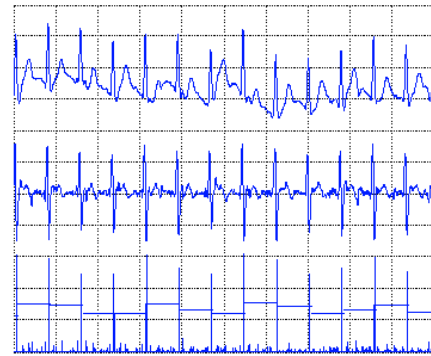


Fig. 4. Heartbeats are detected by the downward signal amplitude. The threshold is one half of the amplitude of the previous heart beat detected. Top: original ECG signal (obtained by integrating the differentiated signal). Middle: Sampled signal (differentiated ECG). Bottom: downward amplitude of the sampled signal (with a horizontal line across it represents the threshold).

least one heartbeat. Its drawback is that it has a high demand for computing power and is time consuming for 8bit micro-controllers, especially when there is no multiplication instructions like the one we used in this design. Therefore, we designed a simple, fast algorithm for heartbeat detection. Firstly, the ECG signal is differentiated by analogue filters with frequency responses shown in Fig. 3 before it is converted to digital data. The signal obtained after A/D conversion is actually the derivative of normal ECG signals. This significantly stabilizes the baseline as previously mentioned. A 40Hz cut-off frequency for the lowpass filter removes most of the high frequency noises such that the heartbeat signal is clean enough for reliable detection without needing extra digital processing. Secondly, once the signal is sampled and converted to digital values, its amplitude is calculated while the signal is decreasing or the signal's derivative is negative (or positive depending on ECG waveform). If the amplitude is higher than a threshold, one heartbeat is detected and the threshold is updated to one half of this amplitude. A problem with this method is that the threshold would stay very high if a very high noise spike was falsely detected (happens when electrode is removed off the skin and put on again). To recover from this situation, the threshold will be gradually reduced if no heartbeat is detected for 2 seconds. The same algorithm is used for step detection as both of them have very similar signal waveforms.

2) Automatic Synchronization

An audio click sound is provided when the runner's heart rate is close to his step rate. It is locked to the runner's heart rate by a fixed time delay (the phase reference). If the runner keeps his step stride synchronized with the provided audio click sound, his step rate will be synchronized with his heart rate by a fixed phase delay. In order not to disturb his existing running pattern and make the transition natural to the runner when the first audio click sound comes, the following procedure is programmed:

1. Reset *the running timer* and *the running state* if no step is detected for 2 seconds (as steps can only be detected during running).
2. Set *the running state* if *the running timer* has not been reset for 30 seconds (which means the subject is running continuously now).
3. Set *the synchronization state* if the heart rate is equal to or greater than the step rate and the difference between the current phase delay and the phase reference is less than 45 degrees if *the running state* is also set.
4. Output an audio click sound after a fixed time delay (phase reference) from each detected heartbeat if *the synchronization state* is set.

B. Application Program Design

On the computer side, all sampled physiological data are displayed and saved to a file on hard disk in real-time. The application program running on PC is written in Microsoft Visual C++ for Windows. The program contains three threads: main

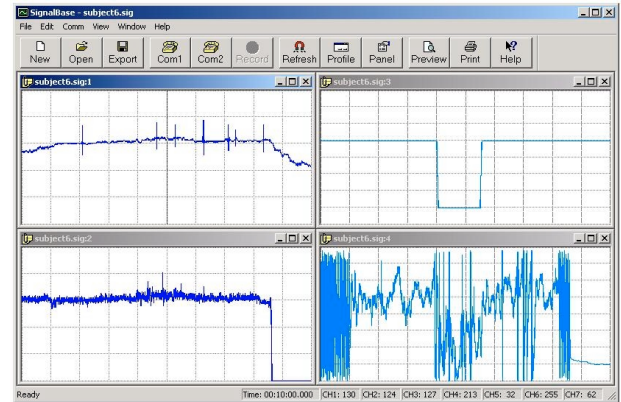


Fig. 5. Example of the display of the application program. Top-left: heart rate, bottom-left: step rate, top-right: phase reference, bottom-right: phase values. (Time scale along x-axis is 2 minutes/section. Scale for y-axis is 45 degrees/section for phase and 50 bpm for step and heart rates).

thread, timer event thread, and data saving thread. The main thread handles the graphic user interface (GUI). A timer is created to initiate the timer event thread every 20 ms.. The timer event thread collects data received by RS232 serial communication port from one of the RF transceivers connected to it. The received data is stored in a circular data buffer and a data buffer block. The main thread obtains data from the circular data buffer and displays them graphically on the screen. There are two data buffer blocks used alternatively. When one of them is full, the saving thread will be created to save it to a file on the hard disk. The program has been running on a Pentium-90 computer without losing any data. The following parameters can be changed automatically or manually from the keyboard:

- The gains for each analogue channel.
- The rate of the audio click reference signal.
- The phase reference when the audio click signal is synchronized with the heart beat.
- Ten running protocols can be programmed by users. It specifies the expected parameter values and the time scheduled for them to be changed during running.

IV. RESULTS

Fig. 5 shows one of the results obtained when the device was worn by runners during a treadmill running test. The running protocol was programmed as follows:

- Set the phase reference to 225 degree.
- Start running on treadmill at a comfortable speed.
- Increase the speed by 1 km/h after every 1 minute if the heart rate is lower than the step rate. When the heart rate equals or higher than the step rate, the audio click sound will start clicking and the speed will be kept constant until the end of the test.
- Once the audio click sound can be heard from the earphone, the subject should try to synchronize his steps with the click sound as accurately as possible and run for

6 minutes. The audio click sound delays the heartbeat by 225 degrees now.

- Change the phase reference to 45 degrees and run for 3 minutes.
- Change the phase reference to 225 degrees and run for 3 minutes.
- Turn the audio click sound off and continue to run for 3 minutes.
- Gradually reduce the speed and then stop.

IV. DISCUSSION AND CONCLUSION

An ambulatory monitoring device has been presented which can measure the heart rate, step rate and respiration signal during running exercise. From Fig. 4, it can be seen that heart rate and step rate detection were reliable during running (sharp changes in heart rate indicates arrhythmia conditions). The audio click sound is locked to the heartbeat only when the phase difference is within 45 degrees of the required phase reference. Therefore, the subject's running pattern is not disturbed when the earphone suddenly starts giving the click sound. It is expected that this ambulatory monitoring device will contribute to research studies on human cardiovascular performances during running exercise.

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